Bacterial chemotaxis in nutrient replete environments

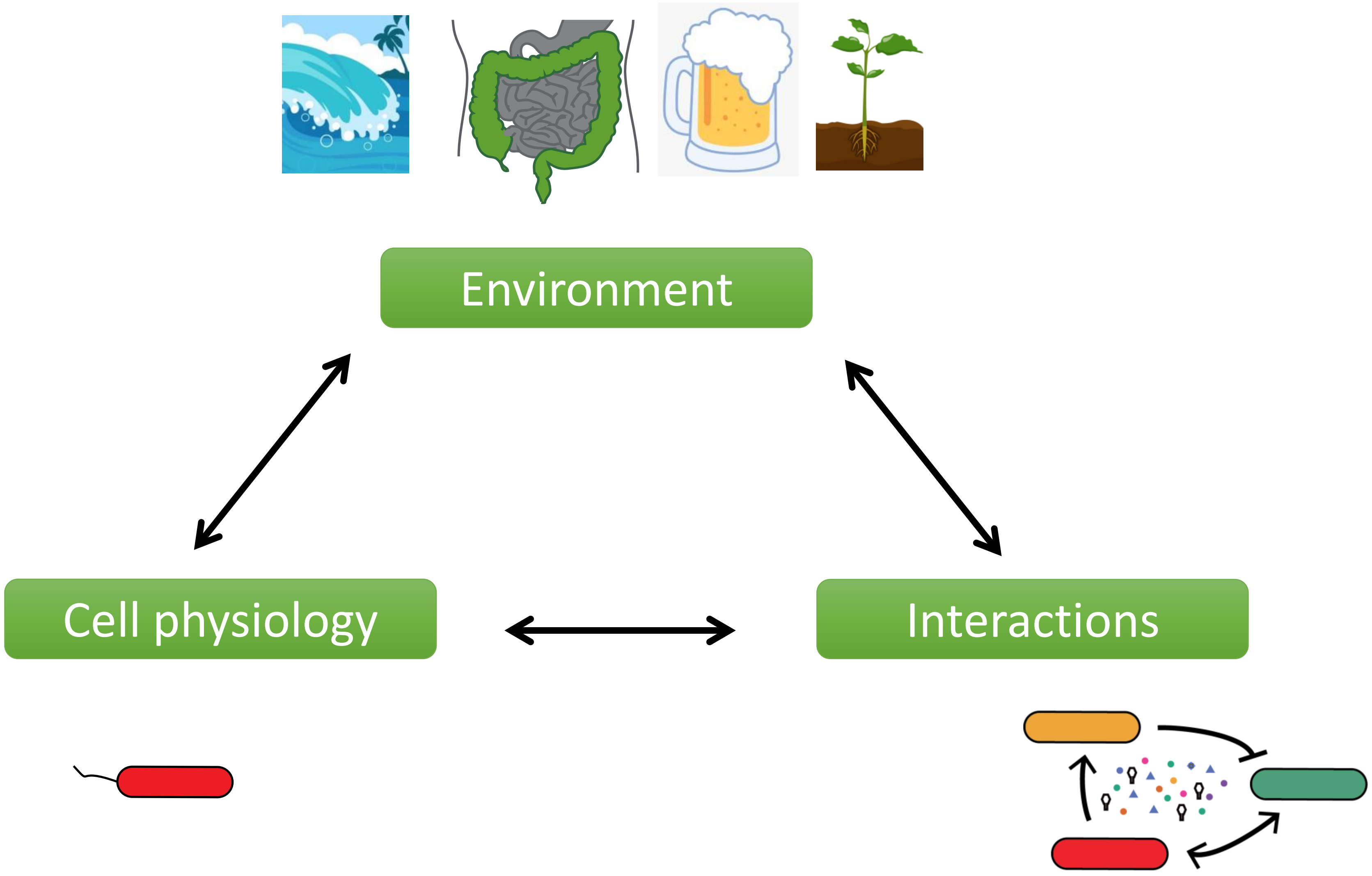
Jonas Cremer
Groningen Biomolecular Sciences and Biotechnology Institute
From Jan 2020 in Stanford

Physics LMU Munich
November 2019

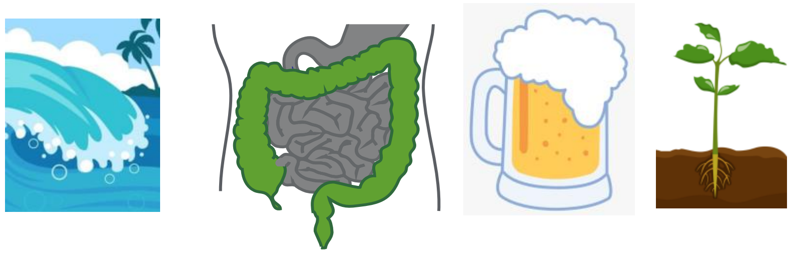
www.bacterialphysiology.com

Postdoc positions available!

Microbes and their communities



Microbes and their communities

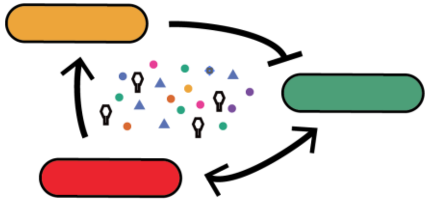


Environment

This talk:
swimming

Cell physiology

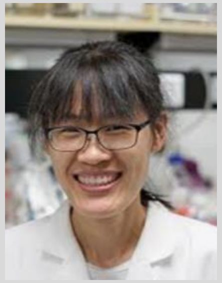
Interactions



Acknowledgements

Chemotaxis

Tomo Honda
UCSD



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CAS Shenzhen

Terry Hwa
UCSD

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CAS Shenzhen

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UCSD

Mini-gut (UCSD)

Alex Groisman

Igor Segota

Zhongge Zhang

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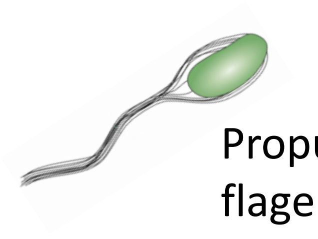
Bacterial chemotaxis: sensing and movement along gradients

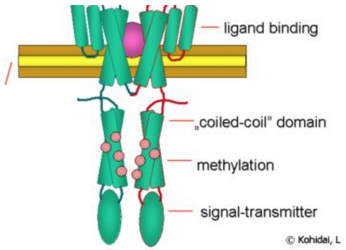
Bacteria swim



Propulsion by flagella-rotation

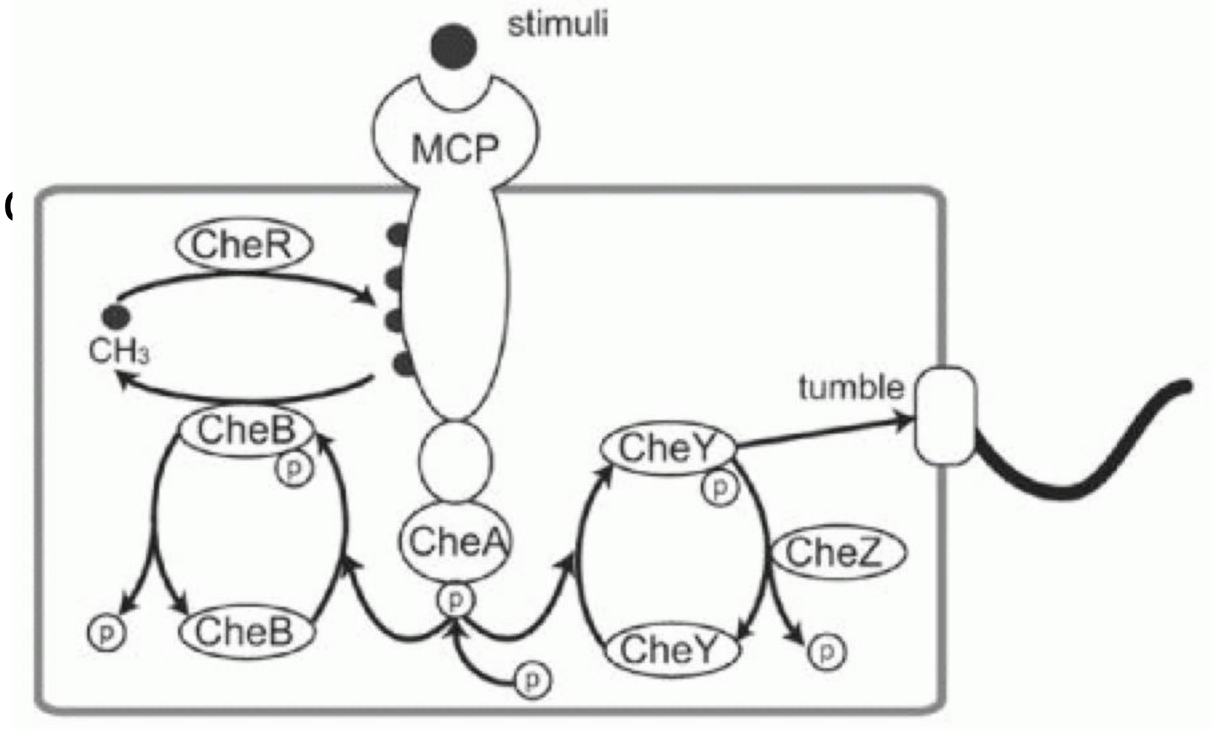
Bacteria sense

For E.coli:
- amino acids
- oxygen
- carbohydrates
- …



aspartate receptor

Bac

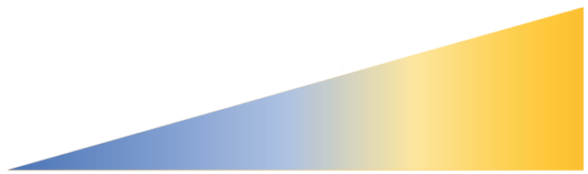


Chemotaxis

What is the physiological role? Advantage of chemotaxis for bacterial cells and populations?

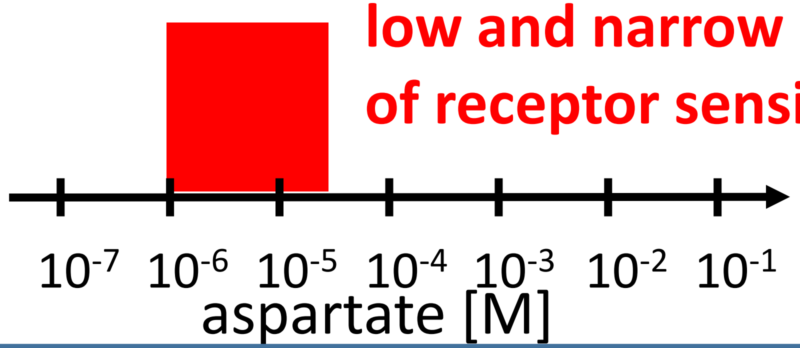
Chemotaxis is occuring on the population level

Environment sets gradients ⟷ Population sets gradients



attractants (AA, sugars, oxygen) are consumed

Consider aspartate:



low and narrow range of receptor sensitivity

+

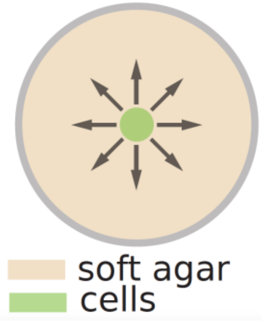
high uptake rate

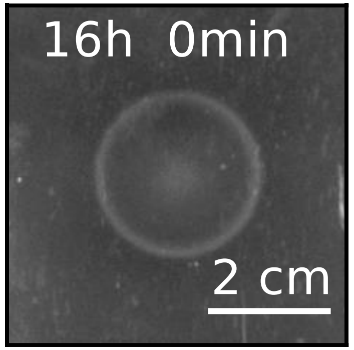
1/1000th of volume occupied by bacteria (OD 1): Detectable range consumed within ~second

→ Bacteria shape the gradients they sense

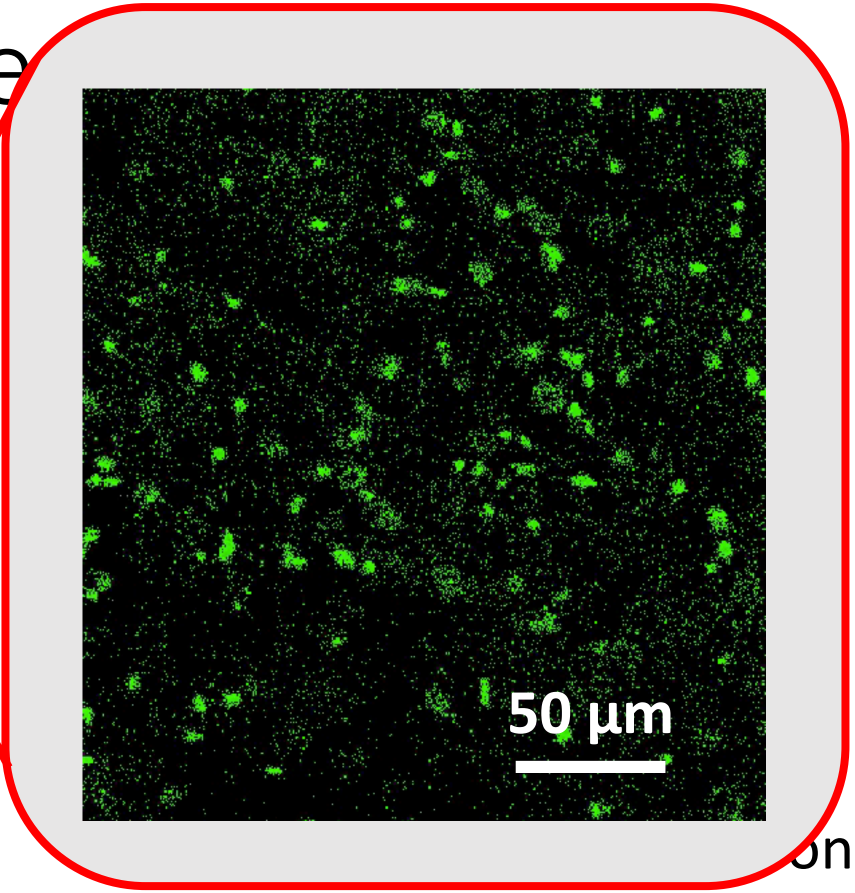
Colony expansion of che

observation in soft-agar: “ring-assay”

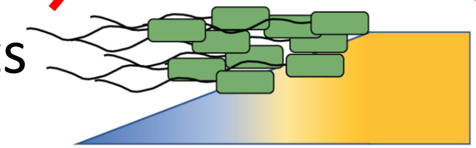




E.Coli K-12; growth condition: glycerol +



Chemotaxis
along gradients



onditions /
physiological state of cells

Many experimental and theoretical studies

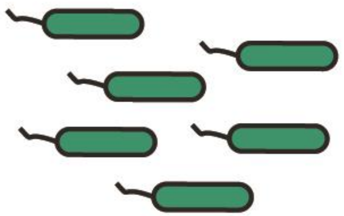
[Keller & Segel, 1971][Lauffenburger, 1984][Jiang et al 2010]
[Saragosti et al, 2011] [Koster et al 2012] [Waite et al
2016][Baym et al 2016][Yi & Dean, 2016][Fraebell et al. 2017]
[Brenner et al, 1998][Saragosti et al, 2010]

Let's understand a simpler scenario first: population expansion without chemotaxis

Modeling expansion without chemotaxis

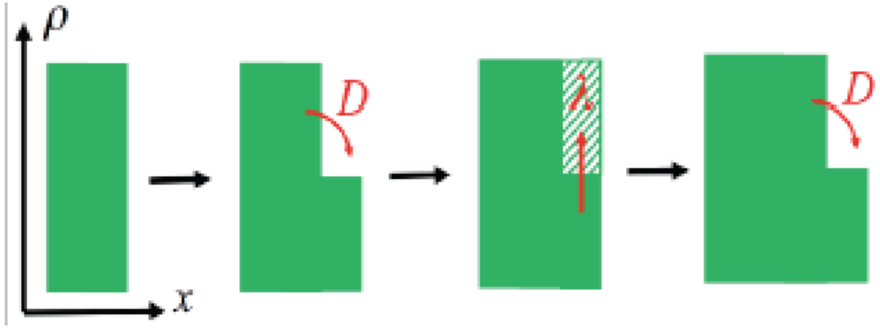
- No attractant: undirected run and tumbling
- Cell growth

cells
$\rho(\boldsymbol{r}, t)$



diffusion: D

growth: λ



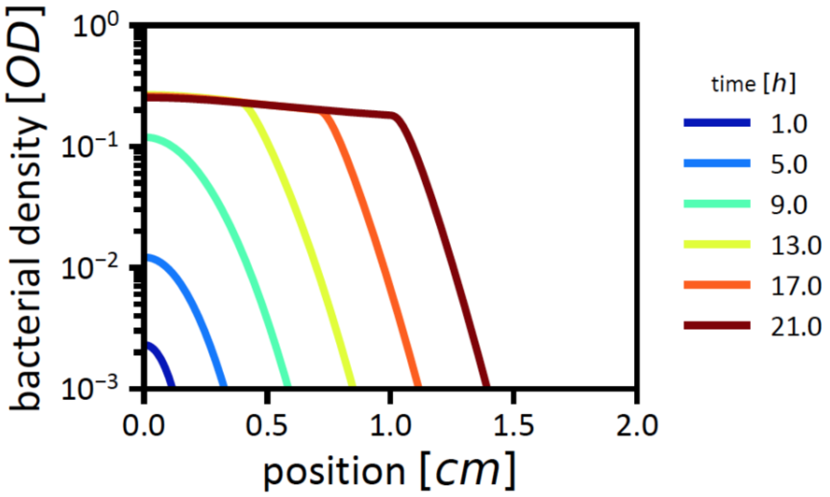
Fisher-Kolmogorov dynamics

$$\partial_t \rho = D\Delta\rho + \lambda\rho(\rho_{max} - \rho)$$

[Fisher 1937, Kolmogorov et al, 1937]

[Andow et al, 1990, Hallatschek et al, 2007, Korolev et al 2012, Gandhi et al 2016] and others

Model predictions:



expansion speed: $u_{FK} = 2\sqrt{D \cdot \lambda}$

slope expansion front: $k = \sqrt{\frac{D}{\lambda}}$

Can we confirm Fisher-Kolmogorov dynamics for swimming bacteria?

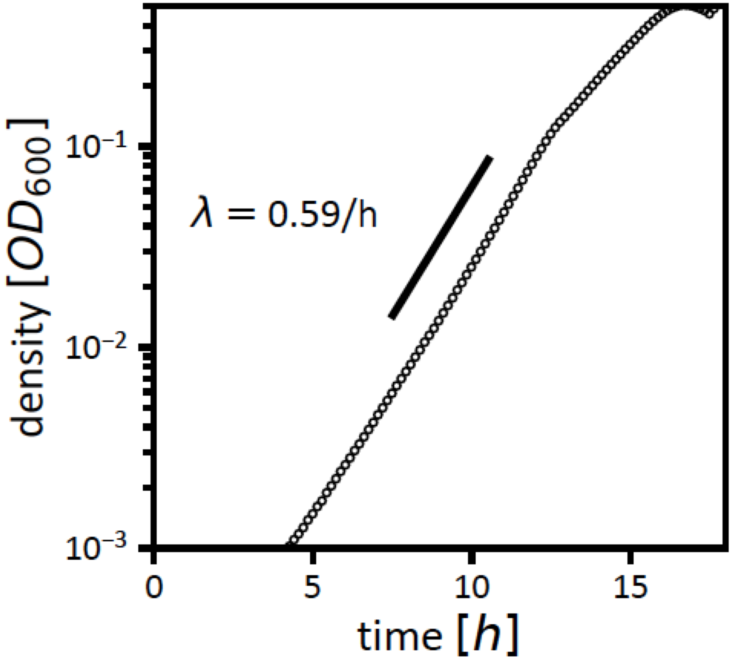
Experimentally: growth in glycerol (not an attractant)

Need to measure cellular diffusion and growth to test predictions

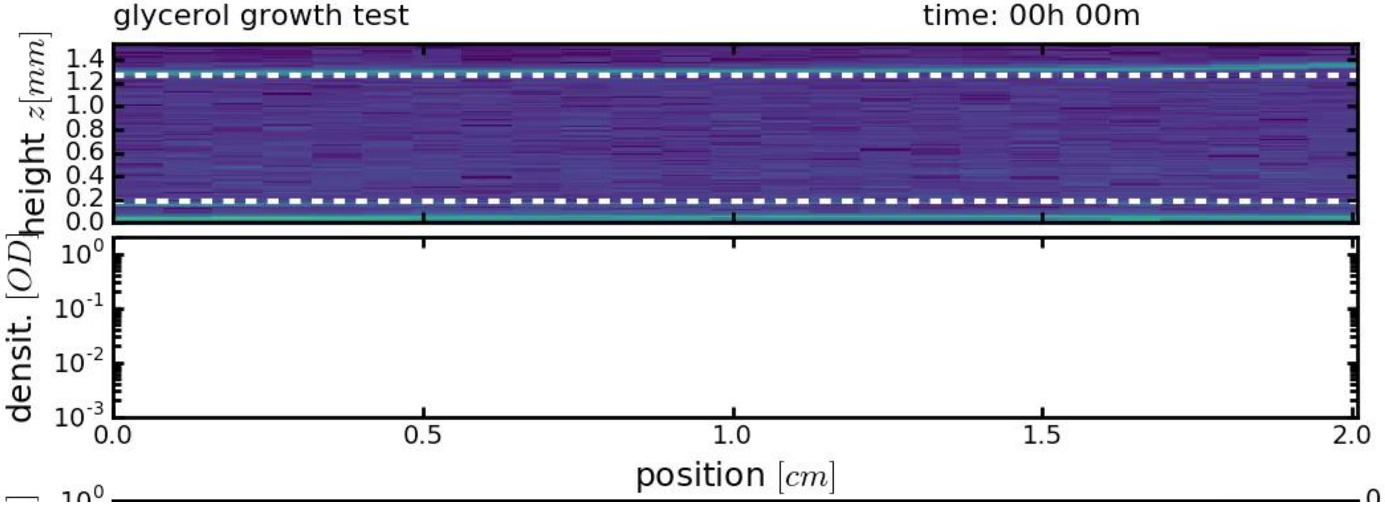
expansion speed: $$u_{FK} = 2\sqrt{D \cdot \lambda}$$

slope expansion front: $$k = \sqrt{\frac{D}{\lambda}}$$

Determine growth rate



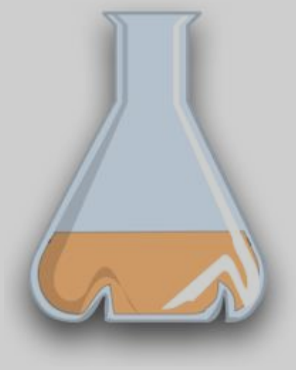
condition: glycerol, no attractant



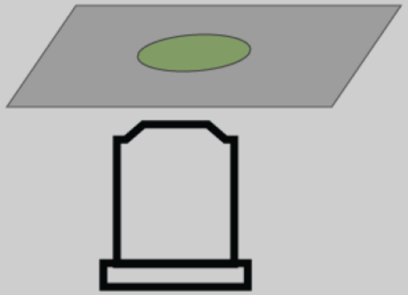
→ Growth rate λ : 0.59 1/h

Side remark: Growing cells swim

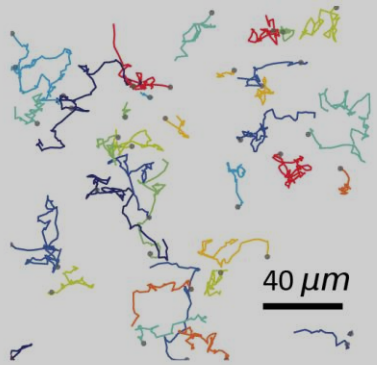
Measure swimming speeds for different conditions



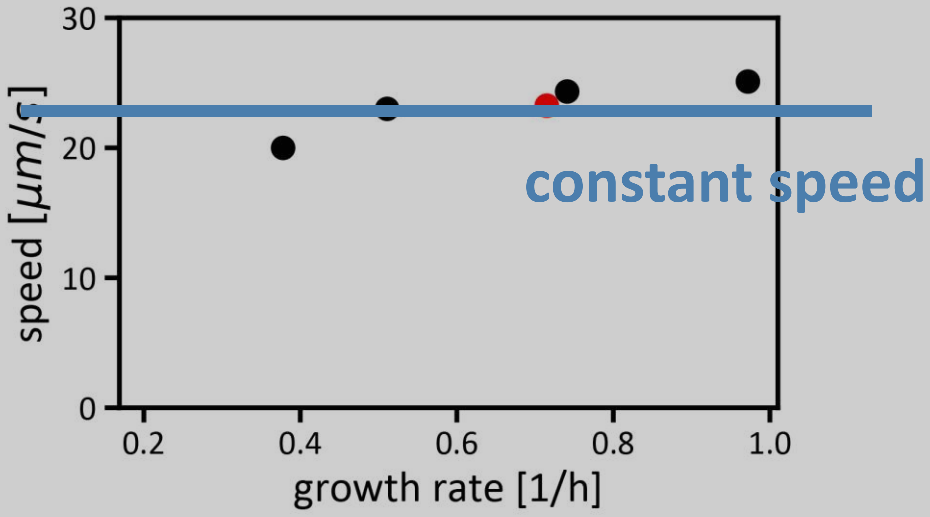
batch
culture



microscopy



trajectory analysis

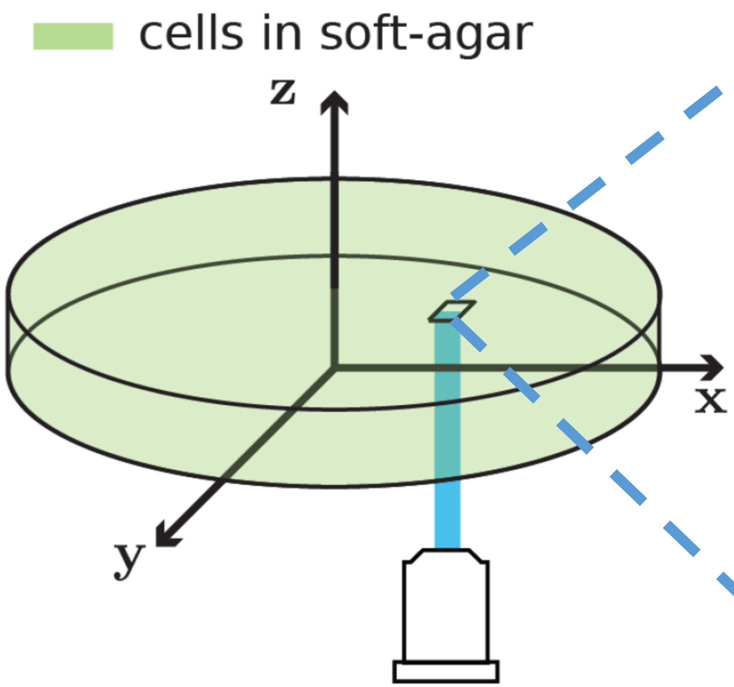


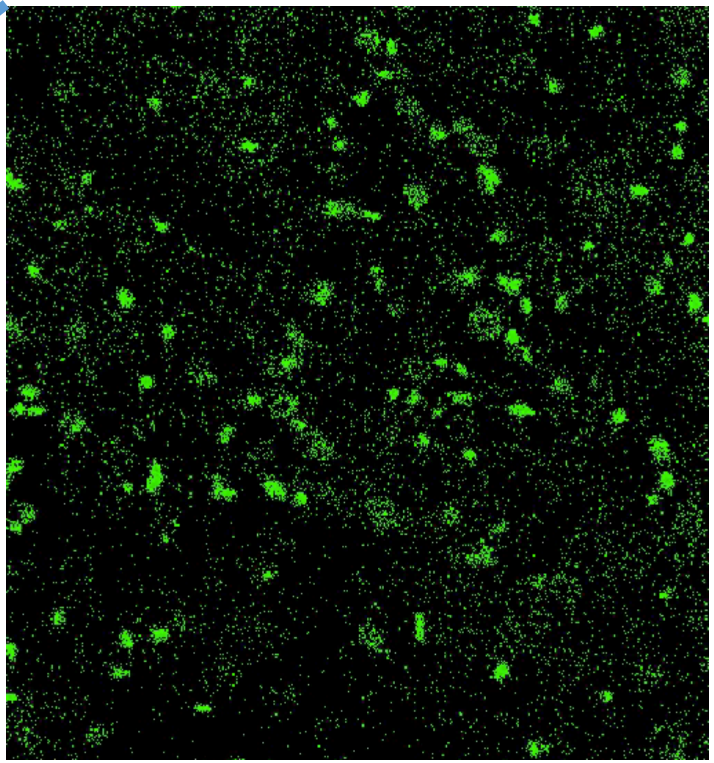
→ **Growing cells swim with constant speed, independent of exact growth condition**

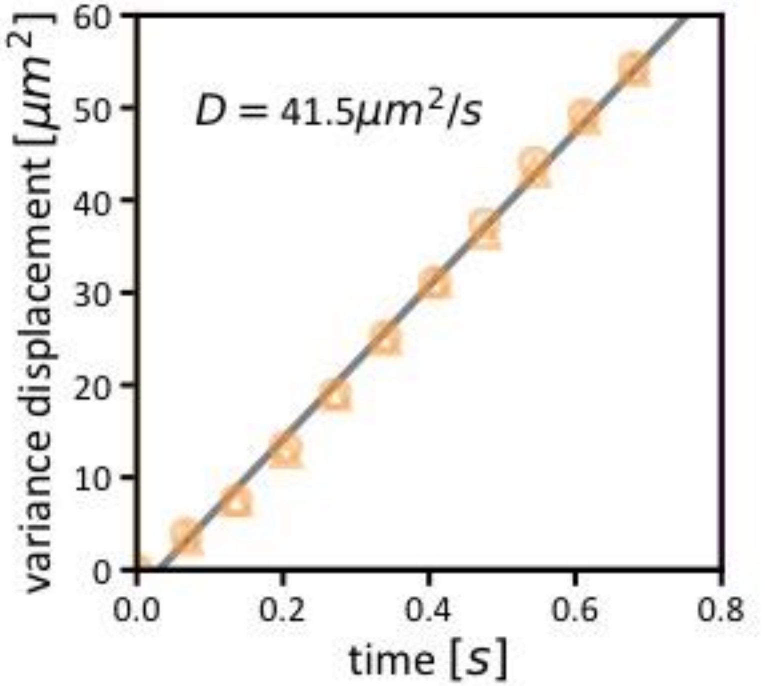
→ Active regulation of swimming behavior

Determine effective diffusion: direct measurement in soft-agar

200 x 200 µm





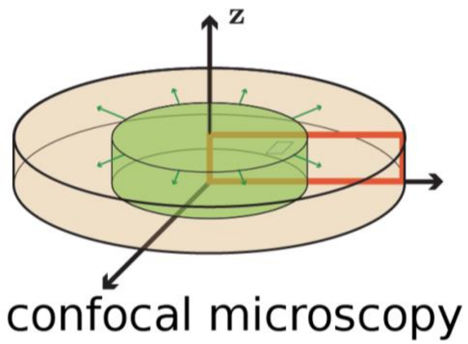


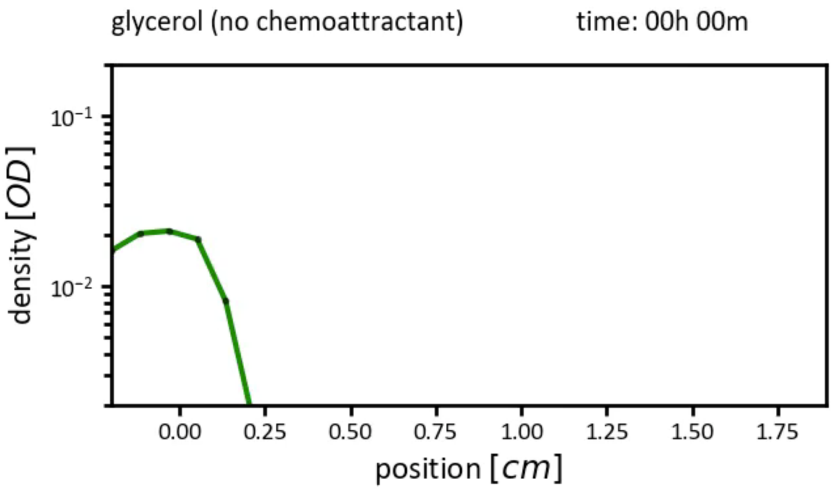
→ Diffusion D : 42 µm²/s

growth in glycerol

Observed expansion without chemotaxis follows Fisher-Kolmogorov dynamics

Observing expansion

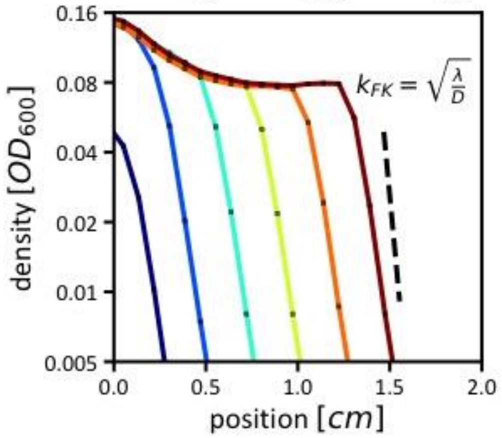


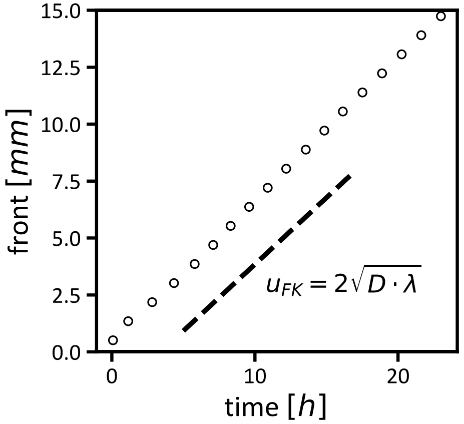


quite fast expansion 0.9 mm/h

Colony of non-motile cells: 0.1 mm/h

Comparison with theoretical prediction





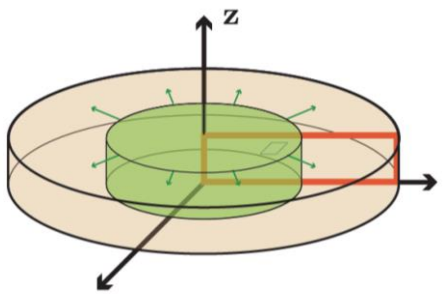
Fisher-Kolmogorov describes expansion

Back to chemotaxis

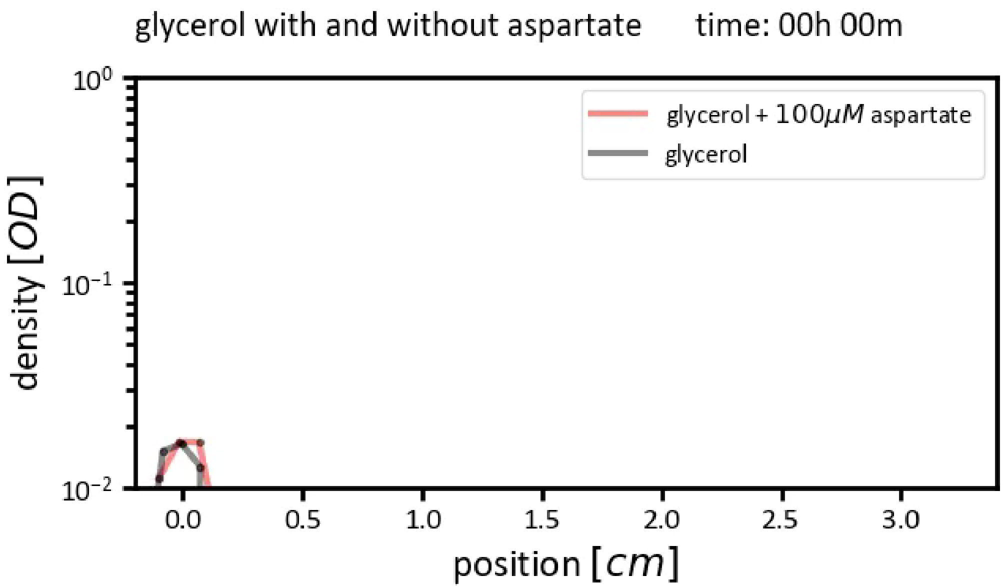
Experimentally: glycerol + aspartate

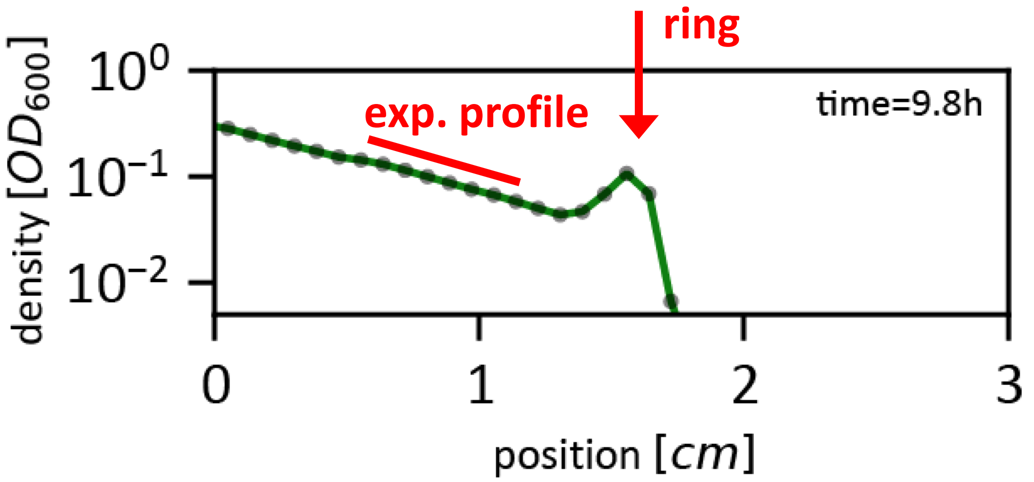
Expansion with chemotaxis: ring and exponential trailing profile

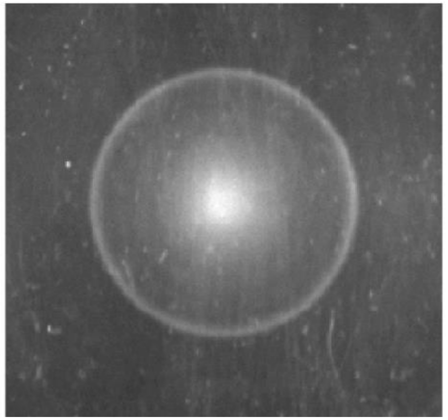
Observing expansion



confocal microscopy



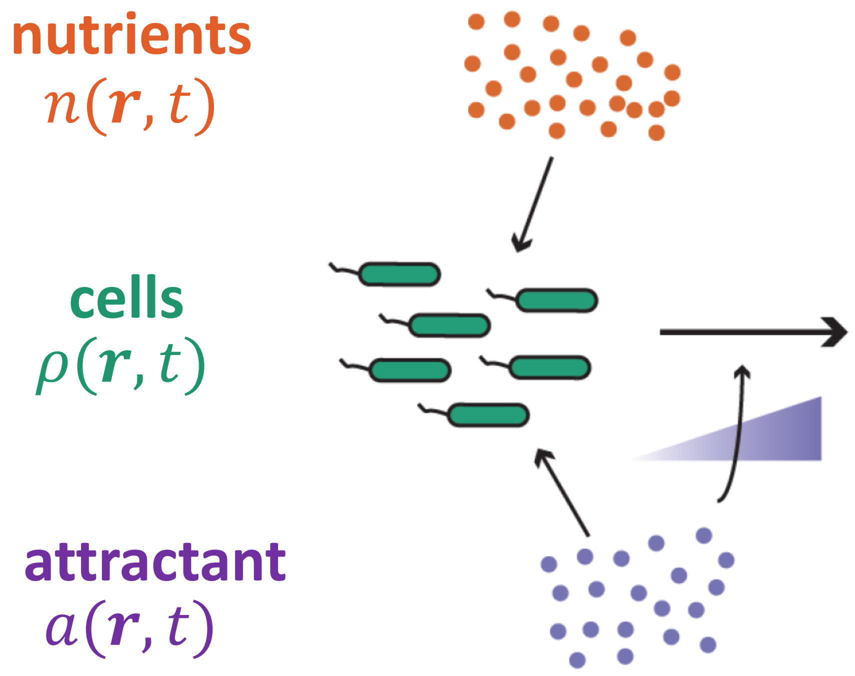




fast expansion:
3.7 mm/h

FK: 0.9 mm/h
Colony: 0.1 mm/h

A new model to describe chemotactic expansion



$$\partial_t n = -\frac{\lambda(n,a)}{Y}\rho + D_{\mathrm{n}}\Delta n$$

$$\partial_t \rho = -\nabla[\,\boldsymbol{v}\rho] + D\Delta\rho + \lambda(n,a)\rho$$

$$\boldsymbol{v} = \chi_0 \nabla \log\left[\frac{1 + {a}/{a_-}}{1 + {a}/{a_+}}\right] \approx \chi_0 \frac{\nabla a}{a}$$

in sensible range

$$\partial_t a = -\mu\rho + D_a \Delta a$$

Only one fitting parameter:

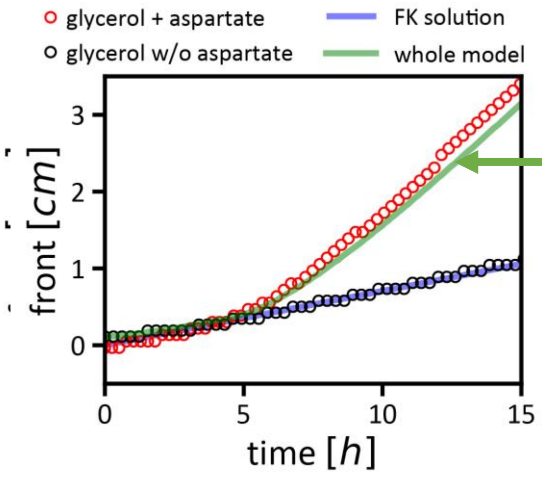
$$\chi_0$$

Crucial modifications of previous models:

- Includes cell growth
- Separation between nutrient and attractant field

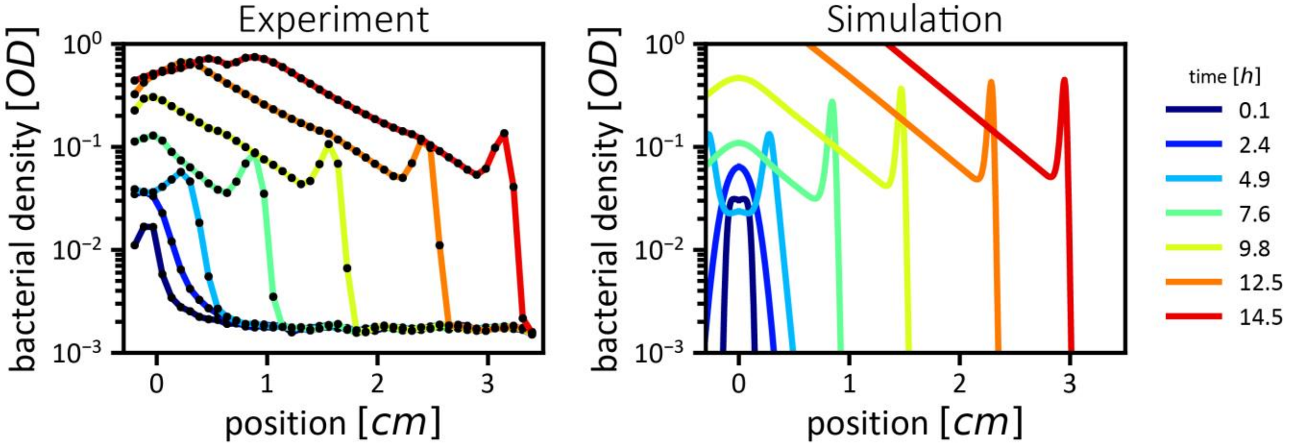
Model predicts expansion dynamics

Reference condition: glycerol + aspartate

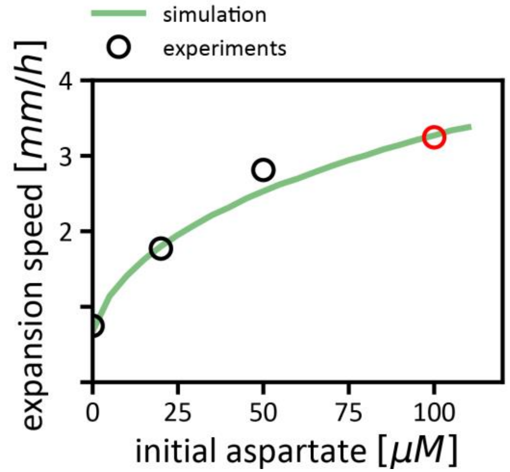


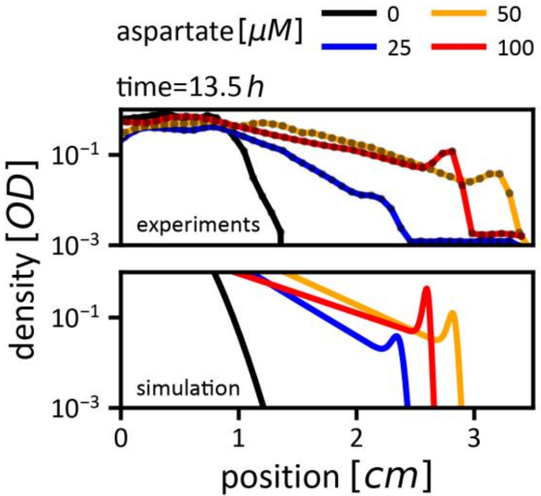
expansion speed matched by fitting

χ_0

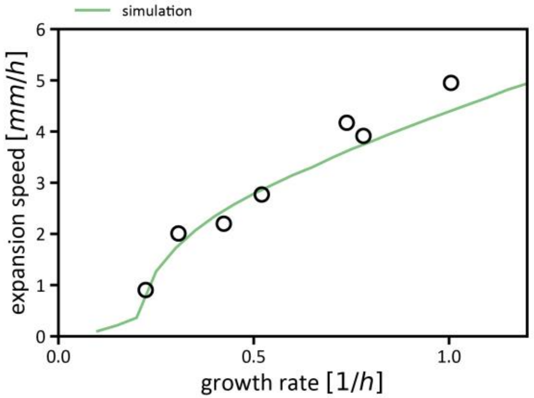


Change in chemoattractant concentration

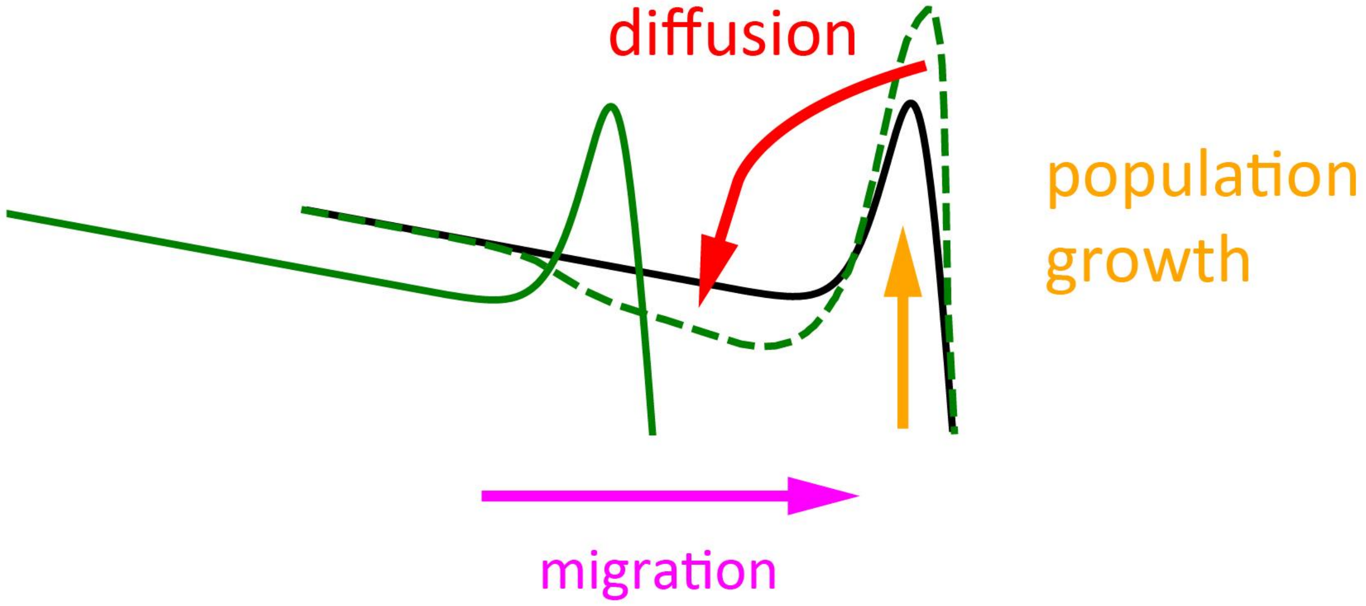




Change in growth rate

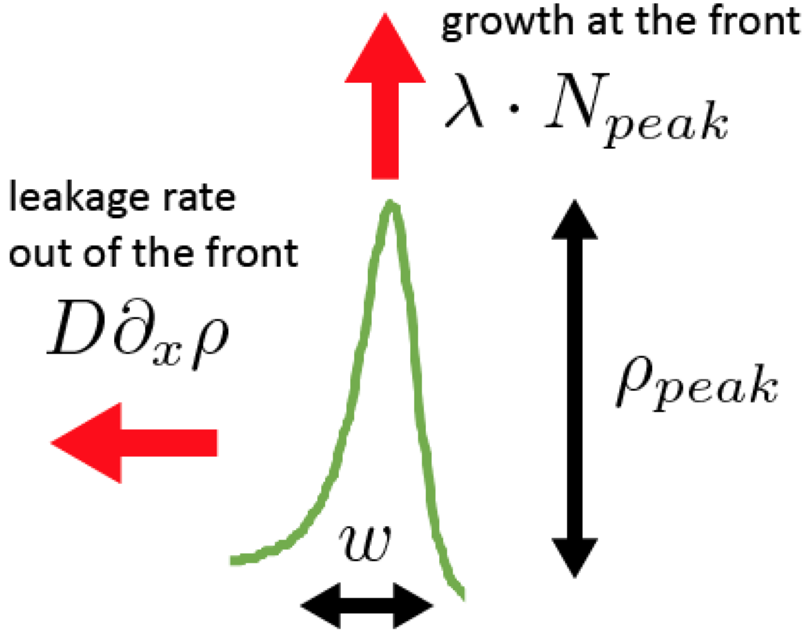


Mode of expansion dynamics



- Growth at front is balanced by diffusion to the back.
- This leads to an efficient seeding of the trailing region
- Growth at the trailing region leads to an exponentially increasing profile

A scaling theory of chemotactic expansion

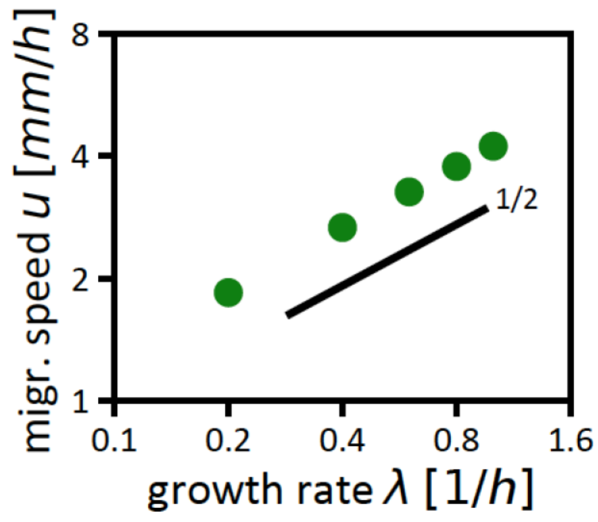


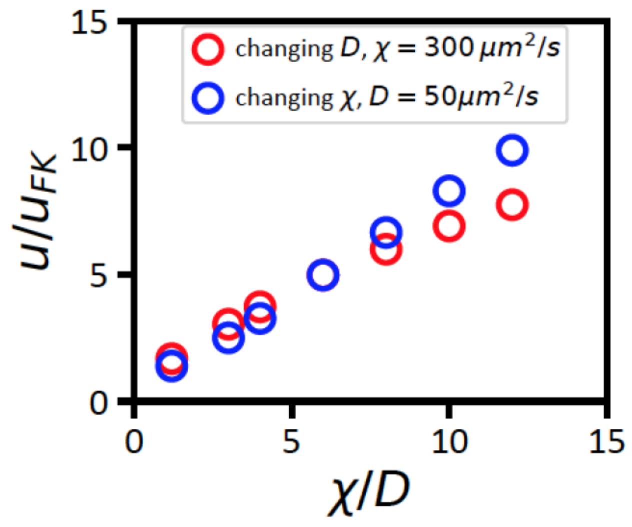
$$N_{peak} \sim \rho_{peak} \cdot w$$

$$\lambda \cdot N_{peak} \sim D \cdot \rho_{peak}/w$$

$$u \sim \chi/w$$

$$u \sim (\chi/D)\sqrt{D \cdot \lambda}$$

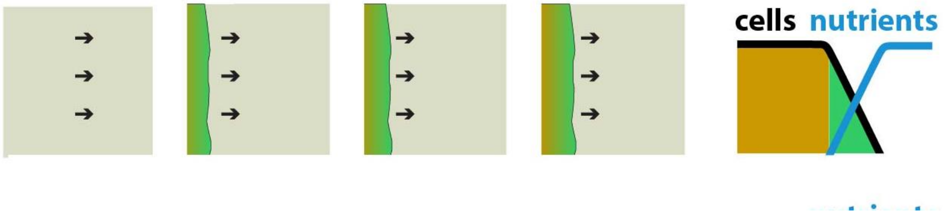




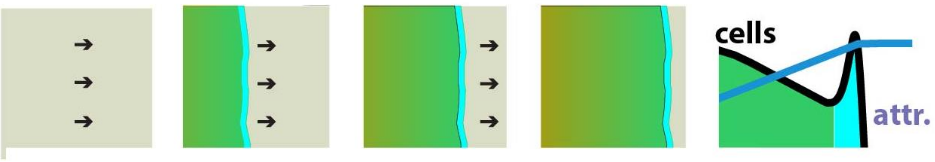
→ Chemotactic range expansion boost expansion speed

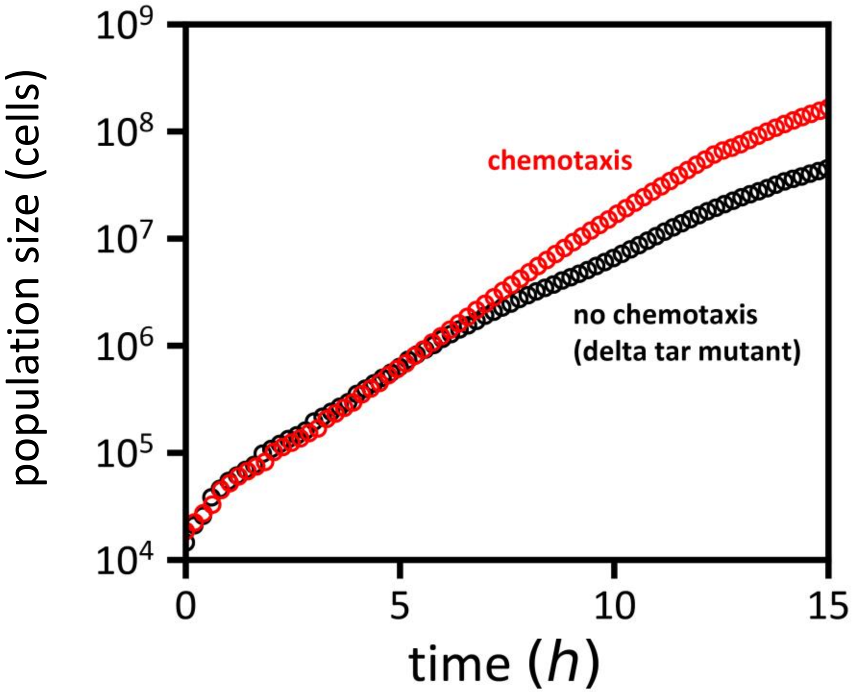
Summary: Chemotaxis as growth strategy to thrive in nutrient-replete environments

unguided range expansion (FK)



navigated range expansion (chemotaxis)





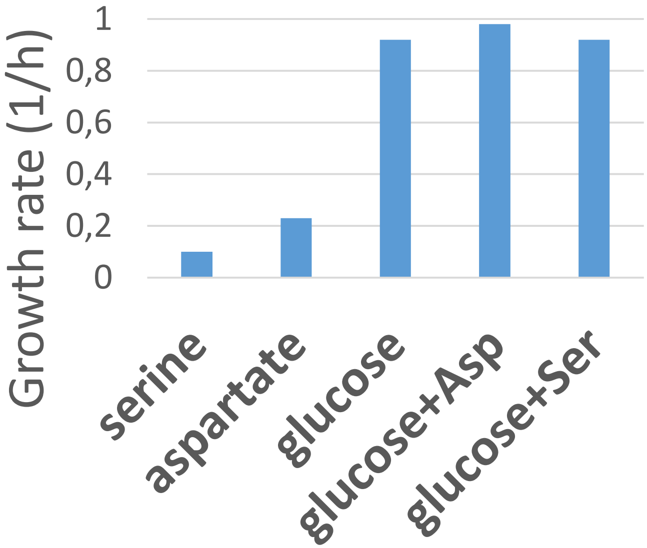
Chemotaxis leads to fast expansion via self-generated gradients and is an efficient strategy to grow in nutrient replete environments

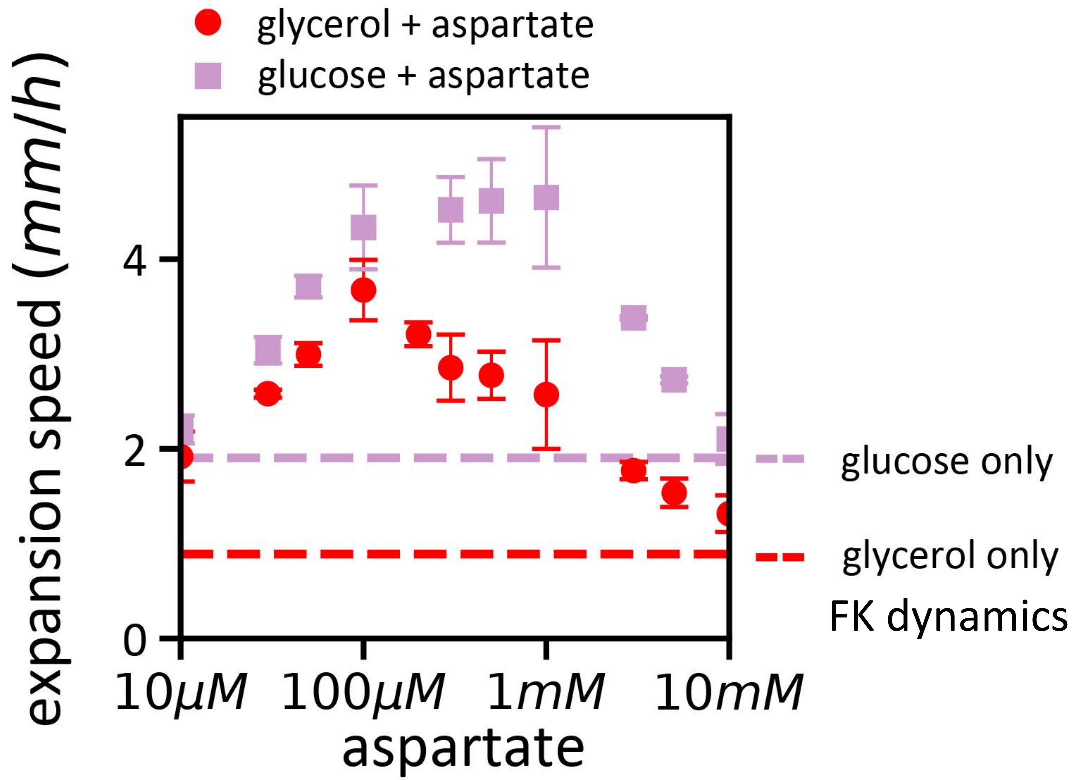
Non-nutritious attractants as cues for navigated range expansion

- A nutrient alone which can be sensed is only weakly increasing expansion speed:

$$u \sim \sqrt{\chi \cdot \lambda}$$

- Separation of nutrient and attractant speeds up migration: $u \sim \chi \cdot \sqrt{\lambda}$
- Good attractants are not good nutrients but rather cues to boost range expansion.





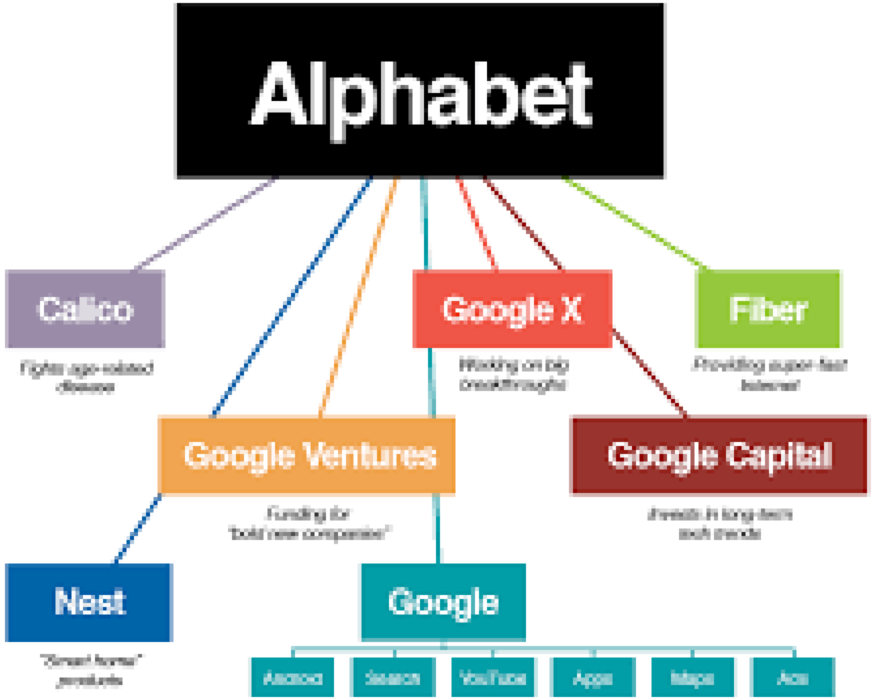
Cremer, Honda, Tang, Wong-Ng, Vergassola, Hwa. Nature (2019)

Oversimplified summary

Canonical hypothesis: nutrient foraging during starvation

Alternative (non-exclusive) hypothesis:

range expansion <u>during good growth conditions</u> (diversification)



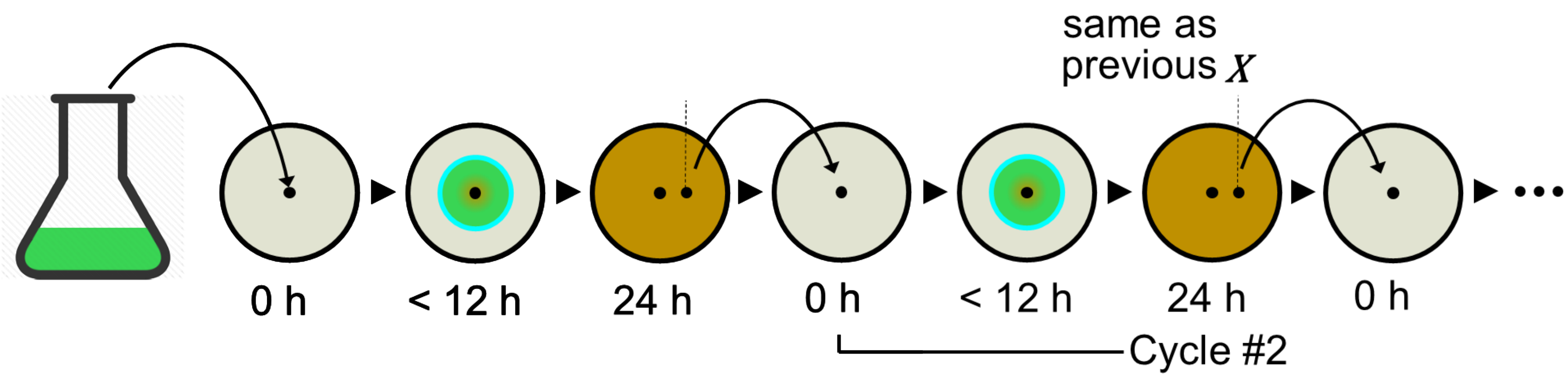
Is there an optimal swimming speed and expansion behavior?

If expansion via chemotaxis increases population growth:

Why are cells not expanding even faster?

Evolutionary study of swimming behavior

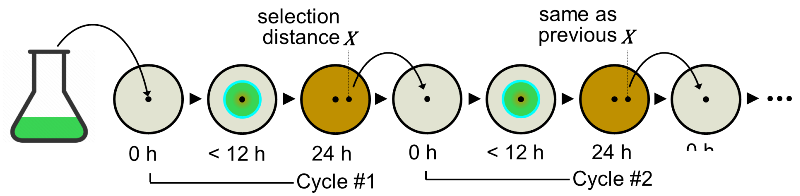
Introduce space dependent selection



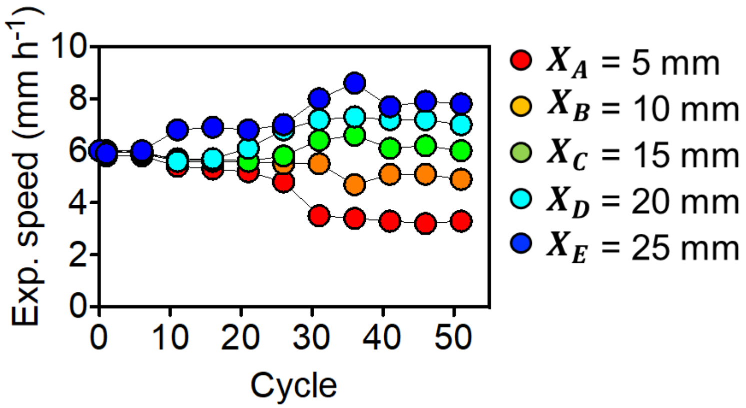
Liu, Cremer, Li, Hwa, Liu. Nature (2019)

Evolutionary study of swimming behavior

Introduce space dependent selection



Evolution depends on selection distance



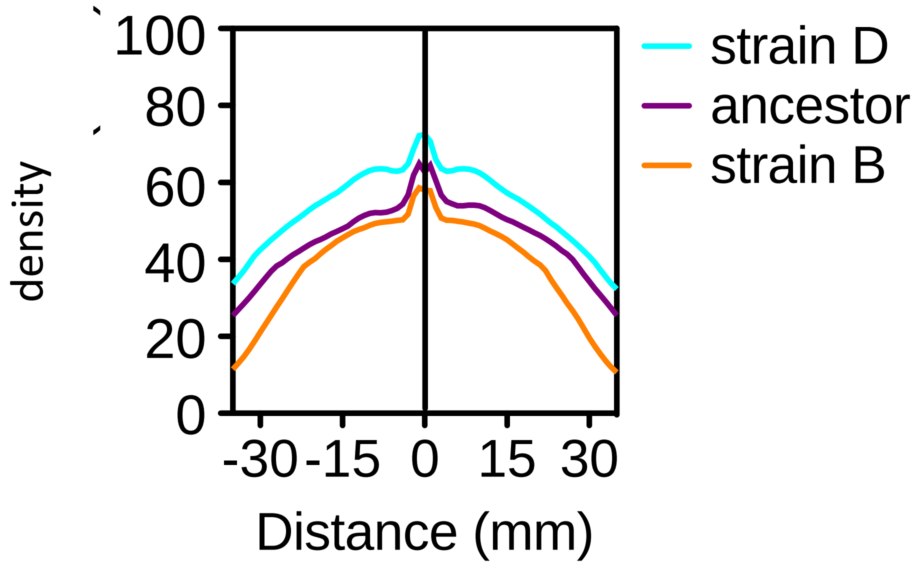
Fast swimming is not always good: optimal swimming depends on typical habitat size cells encounter

Liu, Cremer, Li, Hwa, Liu. Nature (2019)

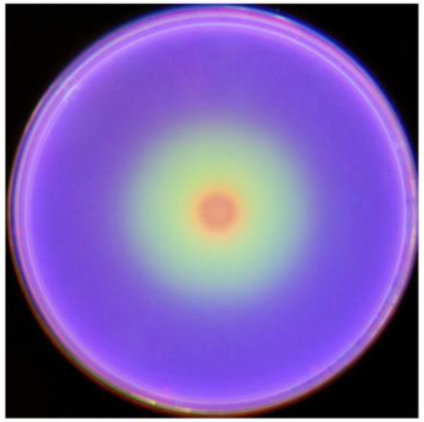
Competition drives local abundance and selection dynamics

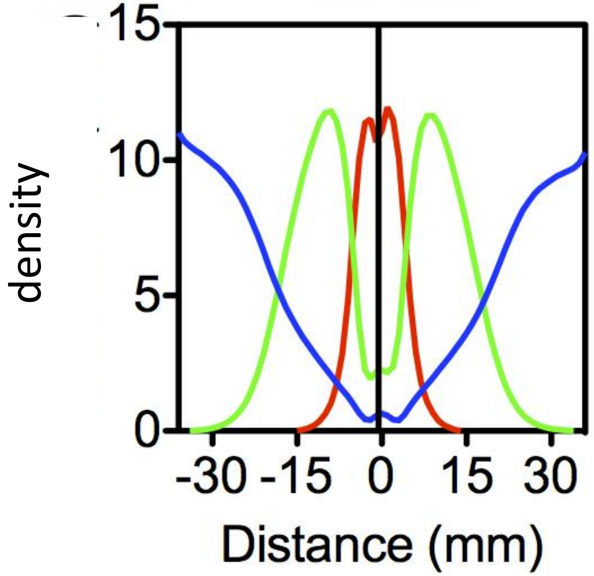
Separate expansion

	strain	ES (mm/h)	GR (1/h)
fast	str. D	7.02	1.96
	anc.	5.92	1.98
slow	str. B	4.32	1.92

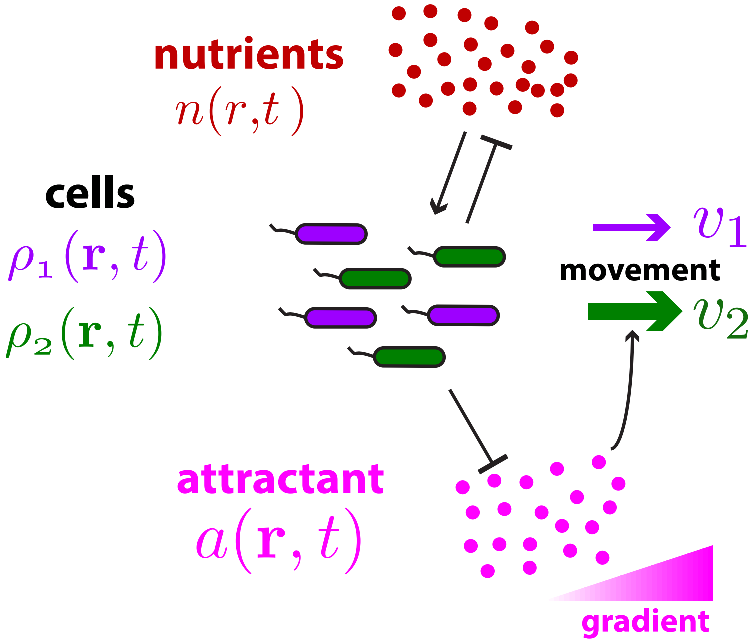


Direct competition





Modeling dynamics



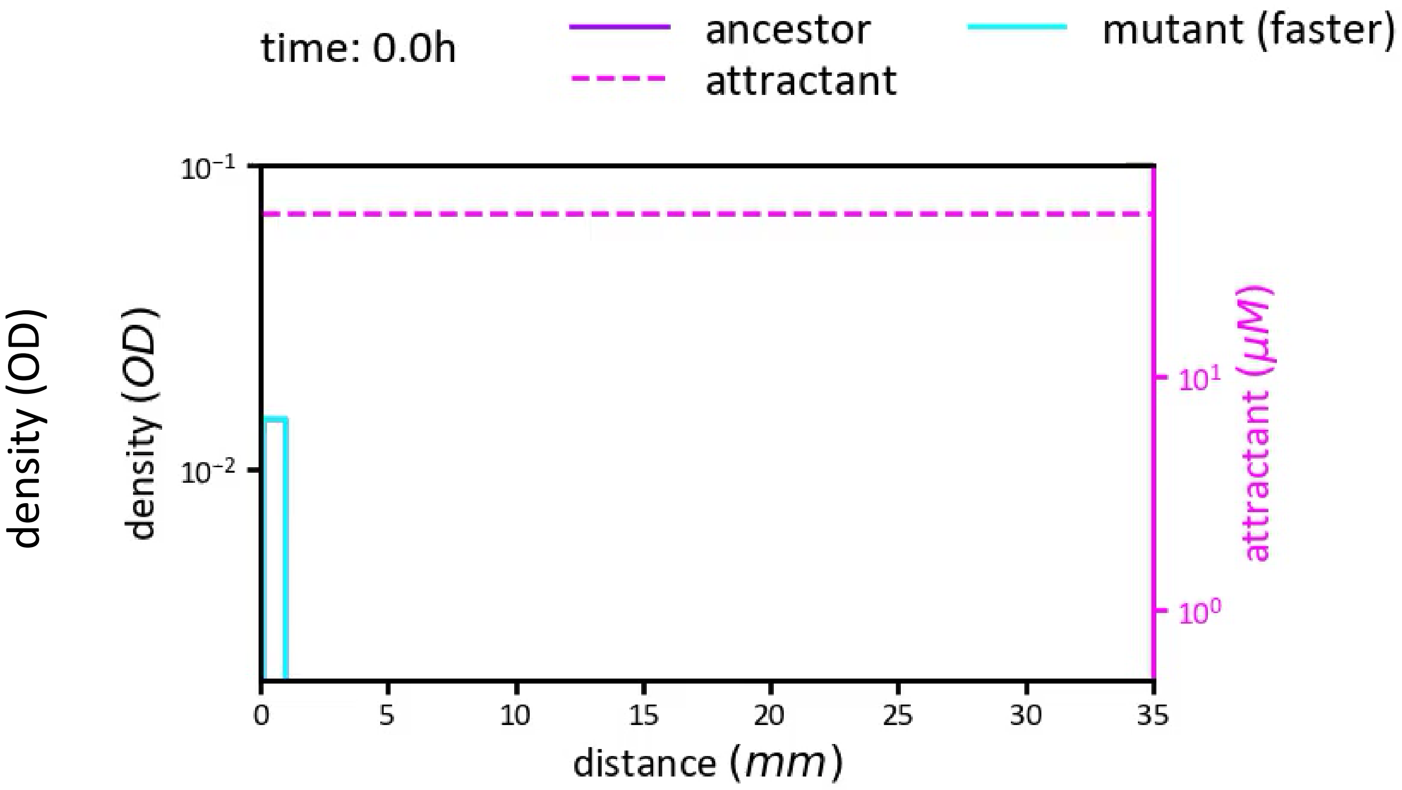
$$\partial_t \rho_1 = D_1 \Delta \rho_1 - \nabla \cdot (v_1\, \rho_1) + \lambda(n) \cdot \rho_1$$

$$\partial_t \rho_2 = D_2 \Delta \rho_2 - \nabla \cdot (v_2\, \rho_2) + \lambda(n) \cdot \rho_2$$

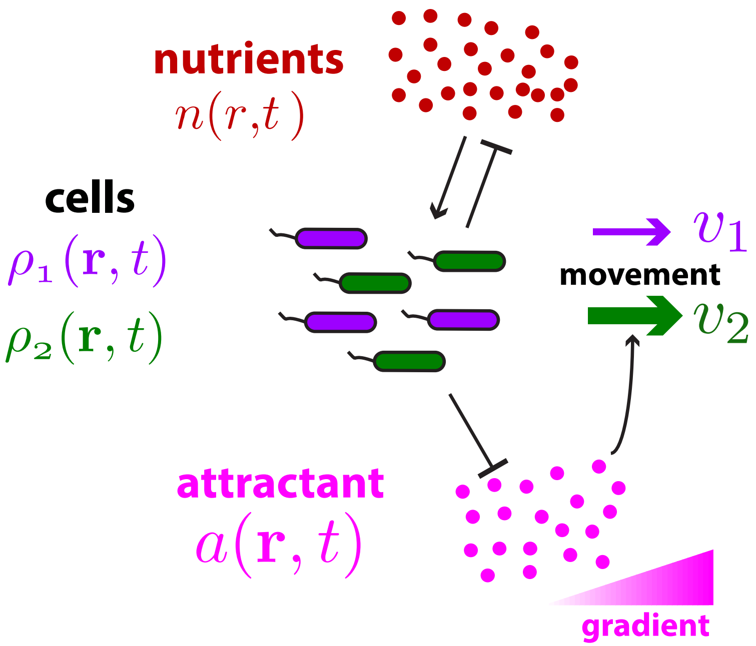
$$v_{1,2} = c_{1,2}\, \nabla \log \left(\frac{1 + a/K_I}{1 + a/K_A} \right)$$

$$\partial_t a = D_0 \Delta a - \mu(a) \cdot (\rho_1 + \rho_2)$$

$$\partial_t n = D_0 \Delta n - \lambda(n) \cdot (\rho_1 + \rho_2)/Y_n$$



Modeling dynamics



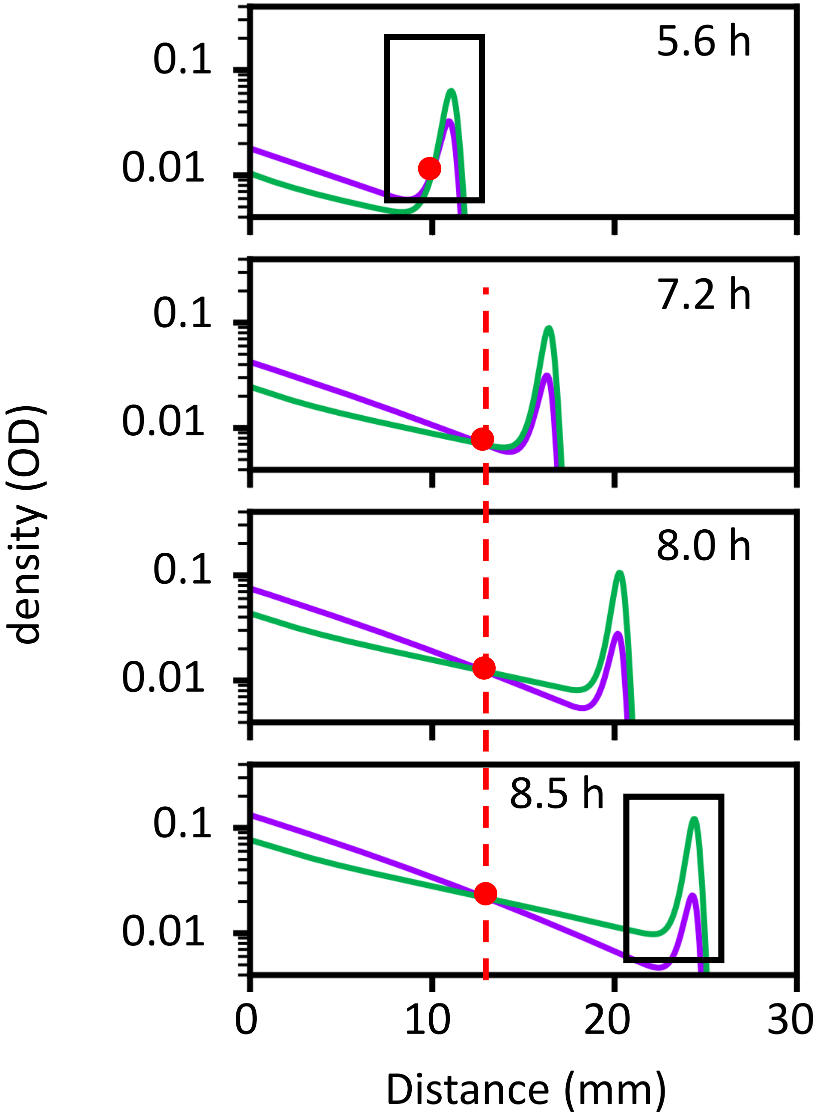
$$\partial_t \rho_1 = D_1 \Delta \rho_1 - \nabla \cdot (v_1\, \rho_1) + \lambda(n) \cdot \rho_1$$

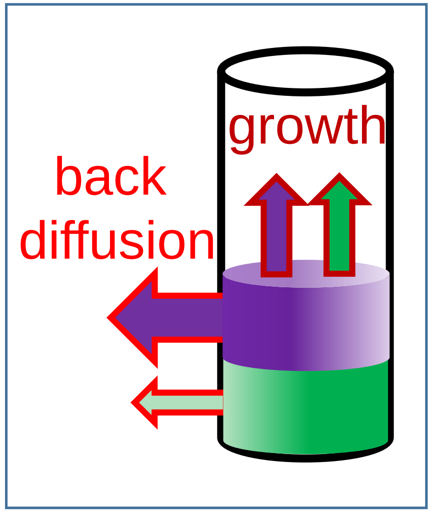
$$\partial_t \rho_2 = D_2 \Delta \rho_2 - \nabla \cdot (v_2\, \rho_2) + \lambda(n) \cdot \rho_2$$

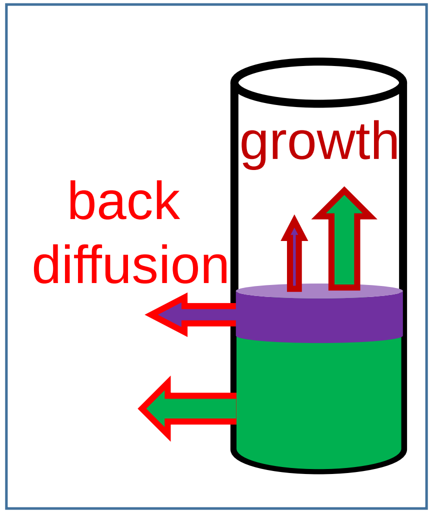
$$v_{1,2} = c_{1,2}\, \nabla \log \left(\frac{1 + a/K_I}{1 + a/K_A} \right)$$

$$\partial_t a = D_0 \Delta a - \mu(a) \cdot (\rho_1 + \rho_2)$$

$$\partial_t n = D_0 \Delta n - \lambda(n) \cdot (\rho_1 + \rho_2)/Y_n$$

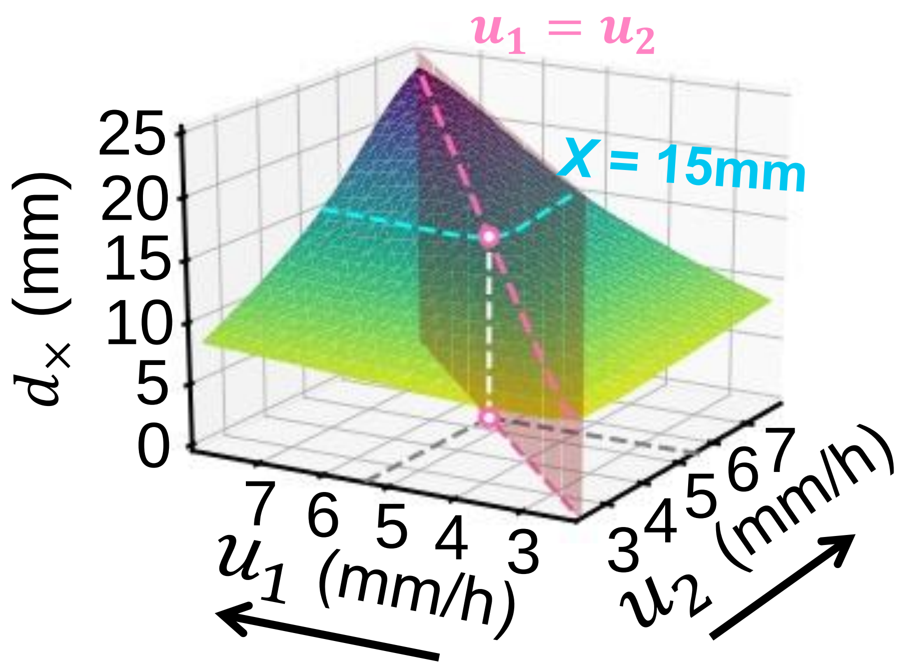


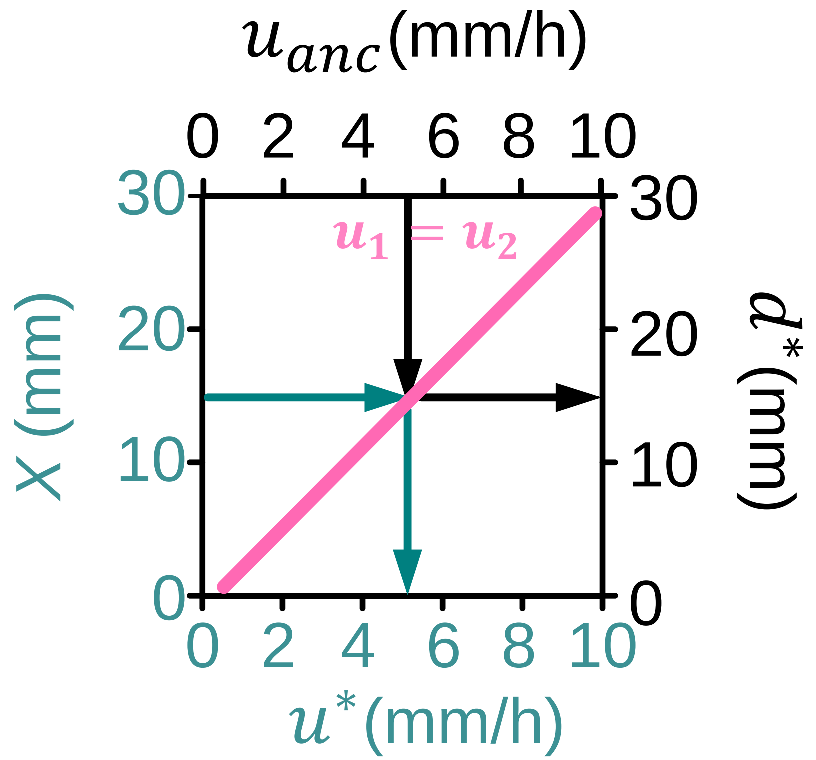




Stable attractor of evolution

analyzing different expansion speeds





predicted stable attractor:

$$u^*(X) \propto X \cdot \lambda.$$

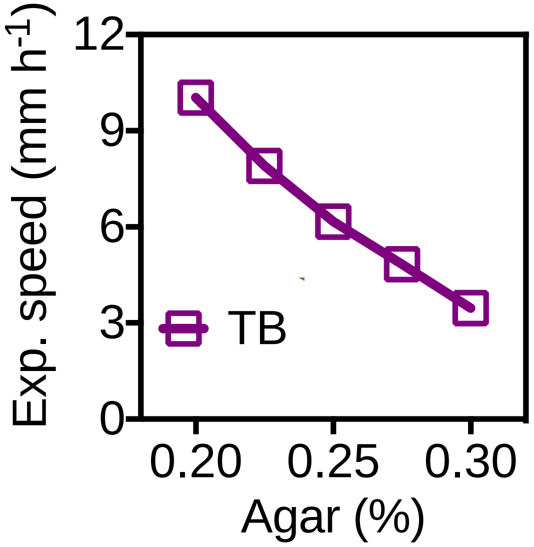
stable expansion speed **position** **growth-rate**

Test model prediction

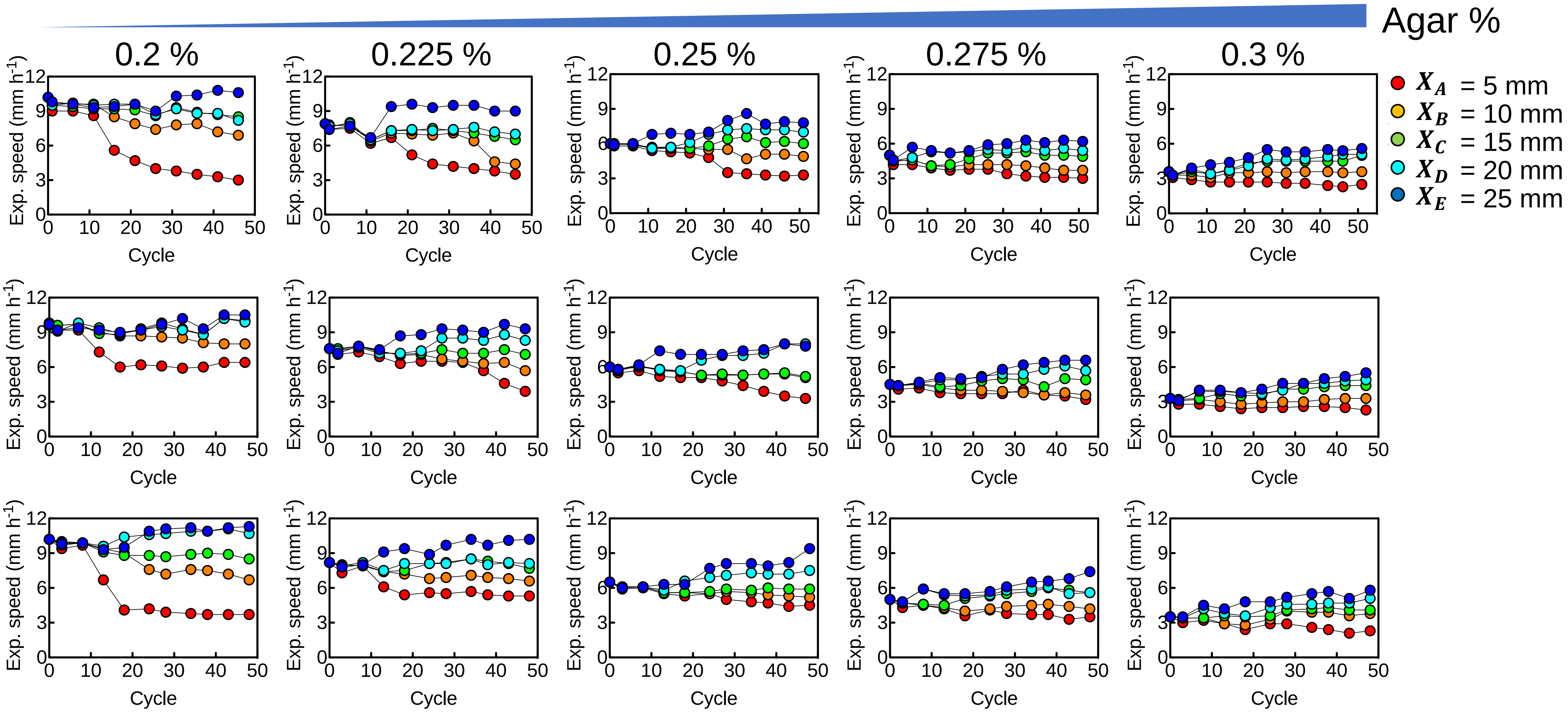
predicted stable attractor:

$$u^*(X) \propto X \cdot \lambda.$$

stable expansion speed **position** **growth-rate**



Evolution in different agar concentrations

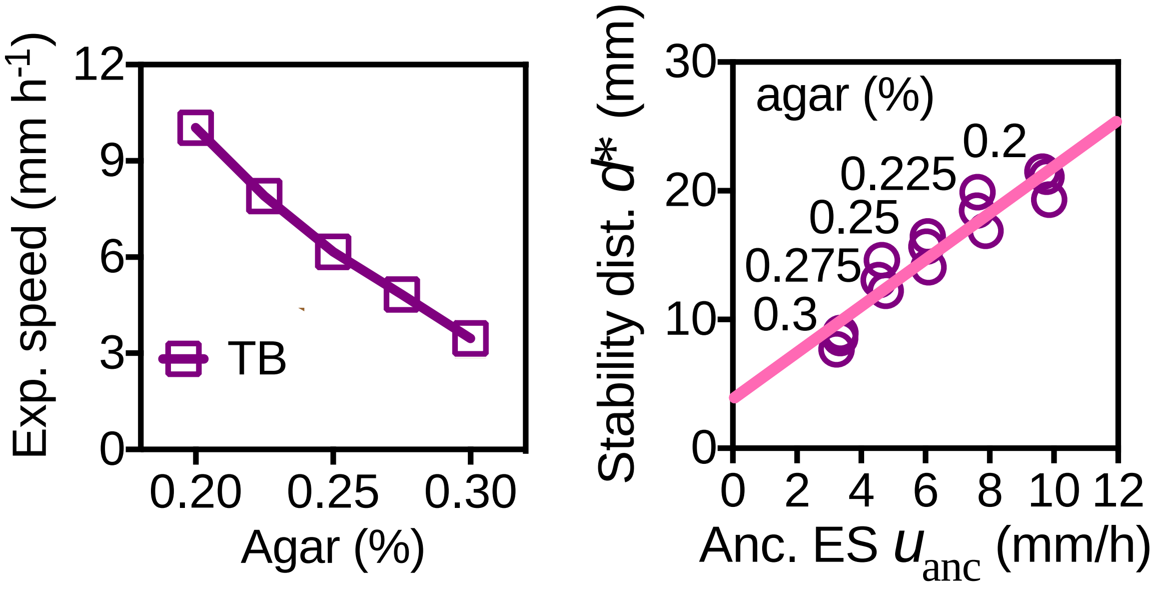


Test model prediction

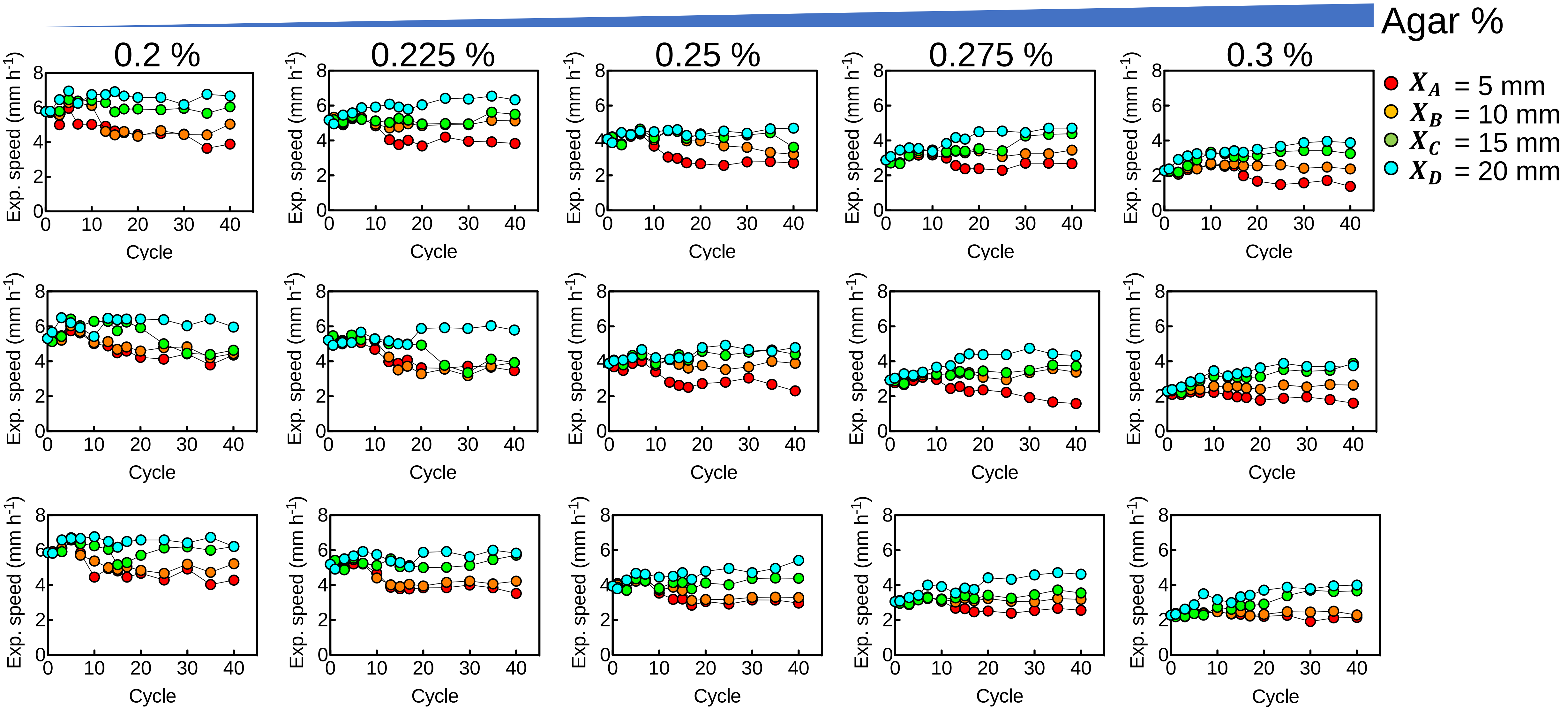
predicted stable attractor:

$$u^*(X) \propto X \cdot \lambda.$$

stable expansion speed **position** **growth-rate**



Evolution in Casamino acids (slower growth)

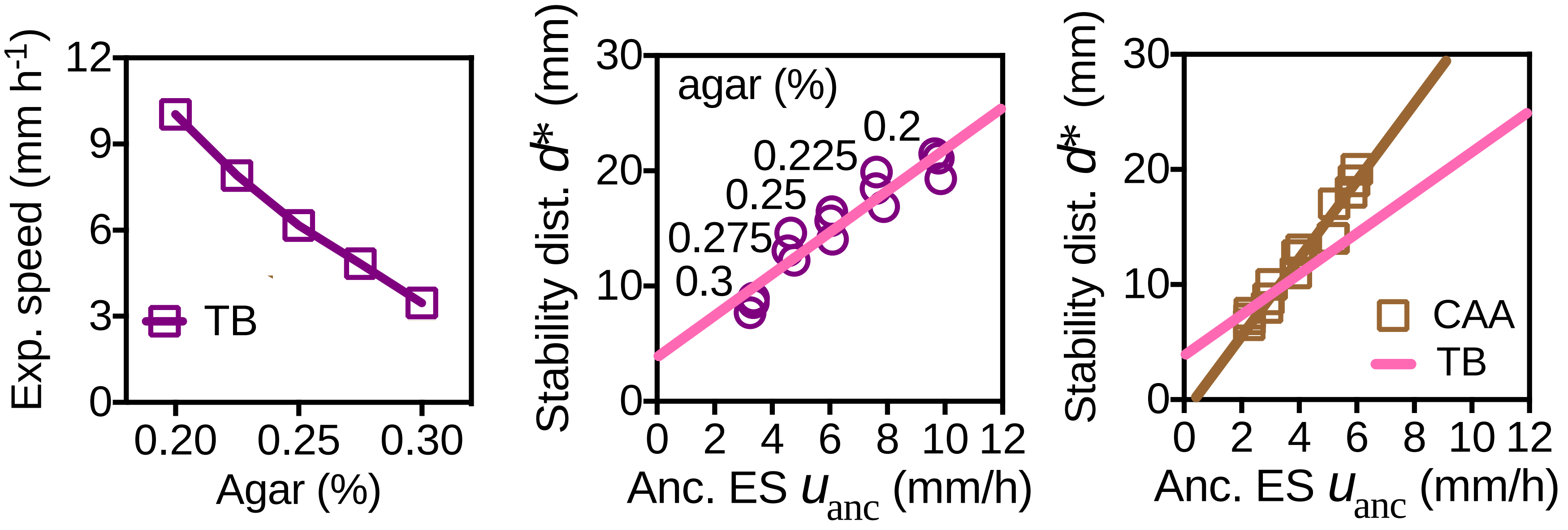


Test model prediction

predicted stable attractor:

$$u^*(X) \propto X \cdot \lambda.$$

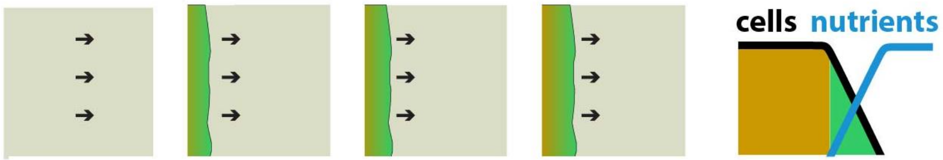
stable expansion speed **position** **growth-rate**



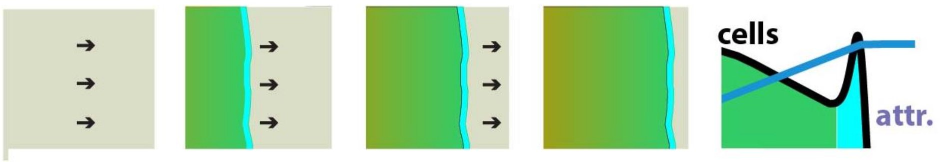
Summary: Chemotaxis as growth strategy to thrive in nutrient-replete environments

Consumption of non-nutritious attractants leads to fast expansion and is an effective strategy to boost colonization into nutrient replete environments

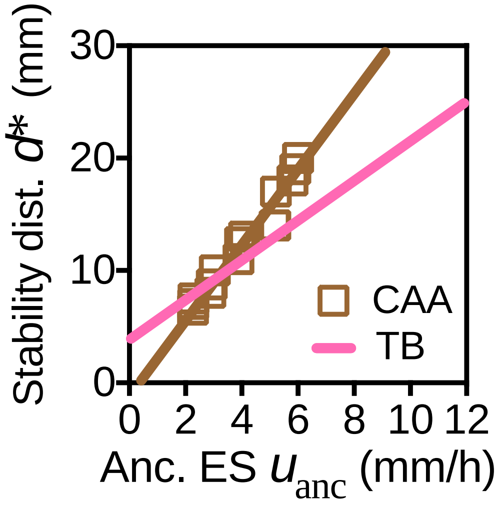
unguided range expansion (FK)



navigated range expansion (chemotaxis)



Competition leads to an optimal expansion speed which depends on habitat size



$$u^*(X) \propto X \cdot \lambda$$

stable expansion speed **size** **growth-rate**

Cremer, Honda, Tang, Wong-Ng, Vergassola, Hwa. Nature (2019)

Liu, Cremer, Li, Hwa, Liu. Nature (2019)

Thank you for your attention!

Postdoc positions available. Contact me for further details.